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PIV Technology for Simulated Turbine Film-Cooling Flows

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September 8-10, 1996

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PIV Technology for Simulated Turbine Film-Cooling Flows

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ABSTRACT: Two-color double-pulsed PIV (Particle Image Velocimetry) was used to investigate turbine film-cooling flows with high freestream turbulence and simulated wake passing. Since the instantaneous realizations of these highly turbulent and unsteady flows are not representative of mean flow behavior, 10 - 30 realizations were typically recorded. The average from these realizations of the film-cooling flows for 1% freestream turbulence was compared with the corresponding hot-wire profile. The PIV images revealed shear-layer structure developing from the film-cooling-hole walls that has not been previously considered in modeling these flows. Improved modeling of the fluid dynamics of interaction and development of these flows (jet-spread and turning) also resulted from this PIV technique.

NOMENCLATURE

d	film-cooling-hole diameter (1.905 cm)
R	coolant blowing (mass-flux) ratio ($\rho_c U_c/\rho_\infty U_\infty$)
Re	Reynolds number based on film-cooling-hole diameter
Tu	turbulence intensity (u'/U)
U	mean local streamwise velocity (m/s)
x	streamwise distance measured from the downstream lip of the injection hole (cm)
y	vertical distance from the injection surface (cm)
f	forcing frequency (Hz)
ω	vorticity, $1/2(\partial V/\partial x - \partial U/\partial y)$ (1/s)
Ω	reduced frequency (freestream velocity/coolant-hole diameter/oscillation frequency)

1 INTRODUCTION

1. PIV has been explored as an initial step for the measurement of unsteady-flow phenomena associated with the film cooling of turbine components. A detailed understanding of these unsteady flow features is important because recent trends in aircraft-engine gas-turbine combustor designs have resulted in short, high-temperature combustors which produce highly turbulent exit flows. As the exit temperature of the combustors is increased to benefit engine-cycle efficiency, effective film cooling of the turbine components downstream of the combustor becomes increasingly important. Bons et al. (1994, 1995) investigated the effect of unsteadiness and high freestream turbulence on film-cooling effectiveness using physical probes including hot wires and thermocouples. Physical probes, however, are hampered by their intrusive nature, limited spatial resolution (pointwise measurements), and spatial averaging. Hence, an effort was made to

assess PIV development and its application to the measurement of unsteady flow phenomena associated with turbine film-cooling flows.

Film-cooling air is injected through rows of small (0.5 - 0.8 mm diameter typical) holes in the blade surface. The cooling air is supplied from the compressor exit flow and is maintained at essentially constant pressure. The Reynolds numbers (Re - based on the coolant-hole diameter of 1.905 cm) investigated for the unforced flow are 20,000 and 40,000. The effect of vane wake on rotor film-cooling flow is simulated by periodic forcing of the film-cooling flows at the reduced frequency (Ω). Typical reduced frequencies of interest are in the range 20 - 200, which translates to 5 - 50 Hz for this large-scale experiment. Phase-locked measurements at 45-deg. increments of the periodic film forcing for freestream turbulence levels (Tu) of 1 and 17% have been made.

PIV has been used for a number of years to measure velocity distributions in planar cross sections of aerodynamic flow fields (Adrian 1991, Lourenco et al. 1989). The advantages of the two-color PIV system used in the present investigation are 1) the directional ambiguity is resolved using the color coding of the particle images, which is inherent in the system. 2) higher data yields and signal-to-noise levels are attainable, and 3) the technique is suitable for both reacting and non-reacting flow fields. The present paper also describes extension of two-color PIV by recording the color images onto a single high-resolution (3060 x 2036 pixels) color CCD camera, thus eliminating the processing time and subsequent digitization time of color film and the complexities associated with conventional image-shifting techniques. For demonstrating the direction-resolving capabilities of this technique and comparing the resolution and accuracy of film vs CCD, a calibration test was performed using a rotating wheel (Gogineni et al. 1996a).

2 EXPERIMENTAL SETUP AND PROCEDURES

2.1 *Facility description*

The open-loop film-cooling wind tunnel, as shown in Figure 1, has been described in detail by Bons et al. (1994, 1995). The main flow passes through a conditioning plenum containing perforated plates, honeycomb, screens, and a circular-to-rectangular transition nozzle. Downstream of the transition nozzle, at the film-cooling station, freestream turbulence levels of 0.7% ($\pm$ 0.05) can be achieved, with velocity and temperature profiles being uniform to within 1%. A single row of 1.905-cm film-cooling holes at an injection angle of 35 deg. to the primary flow was investigated. The length-to-diameter ratio of the film-cooling holes evaluated is 2.4. The ratio of integral turbulence scale to film-hole diameter is in the range 2.88 - 4.23, depending on the turbulence level and turbulence-generation mechanism (Bons et al. 1994). The ratio of momentum thickness to hole diameter typically is 0.05. The ratio of micro scale to film-hole diameter is in the range 0.1 - 0.39. The ratio of temperature or density of the film flow to primary flow is typically in the range 1.07 - 1.09. The variation in blowing ratios (R = 0.5 - 1.5) is achieved effectively by varying the ratio of the film-flow to the primary-flow velocity. For simulation of the vane-wake effects, the film-cooling jet is modulated with a speaker located in the side walls of the coolant-supply plenum.

2.2 *Two-color PIV system*

The two-color PIV system (Gogineni et al. 1996b) uses color for temporal marking of the seed particles in the flow field. For successful PIV measurements in complex three-dimensional flows, the selection and implementation of the proper seeding strategy is a major factor. The seeding particles must be extremely small (typically < 1 μm) to track accelerations in the fluid effectively. In the present experiment, the film-cooling flow is seeded with sub-micron size particles. The green (532-nm) laser output from a frequency-doubled Nd:YAG laser and the red (640-nm) laser output from a Nd:YAG-pumped dye laser (DCM dye) are combined by a dichroic beam splitter and directed through sheet-forming optics. The laser-sheet energy is typically 20 mJ/pulse, with a thickness of < 1 mm at the test section. The temporal delay between the two lasers is dependent upon the flow velocity, optical magnification, and interrogation spot size. It is set at ~ 12 μs for Re = 20,000. A 105-mm micro lens with an f-number of 5.6 is used to record the images. The high-resolution CCD system (each pixel being 9 μm square) allowed optimization of the seeding density for obtaining high-quality PIV images. The details of the CCD system, data analysis, uncertainty analysis, and calibration have been described previously by Gogineni et al. (1996a).

3 RESULTS AND DISCUSSION

Turbine-blade film cooling takes place in a very hostile, unsteady environment where velocity and temperature disturbances exceed 20%. The freestream and film-cooling wall conditions in these flows exceed those encountered in a classical fully turbulent boundary layer. Parameters of interest in this problem include jet spread or film effectiveness, R, Re, Tu, and Ω. Accurate modeling of these flows has proved difficult due to the high-level unsteadiness. Gogineni et al. (1995, 1996b) used the two-color PIV technique to examine the region around the film-cooling hole for 3 diameters downstream and to document the penetration of the film jet, the shear-layer characteristics, and the jet spread for various flow conditions. It was shown that at Re = 20,000, turbulence clearly increases the film spread for R = 0.7. An increased jet spread results in more rapid mixing out of the film-cooling flow. When R < 1.0, it is observed that the shear-layer roll up is the reverse of what would normally be expected. This reverse roll up is attributed to the film-cooling wall boundary layer. A linear relationship between the jet-exit slopes and both Tu and R was also documented for R < 1.0.

In the present experiment, nominally 10 - 30 instantaneous images were obtained for a given flow condition to capture the essence of the flow features and to determine the time-averaged distribution. One of the main problems in utilizing film for PIV measurements is the inability to maintain the absolute coordinates of the recorded features during the digitization process. This occurs because the film cannot be consistently loaded into the film-scanner to the degree required for reproducibility. Thus, a feature in the film flow must be used as a reference or, as in this study, a correlation technique must be used to minimize the difference in the velocities as a function of image overlap. In the latter approach, one of the instantaneous images is chosen as a reference. Each image at a given flow condition is processed and the resulting velocity vectors compared to those of the reference image. The velocity vectors of each image are shifted with respect to the reference-image vectors and the velocity differences calculated. The image coordinates chosen are those which coincide with the image shifts necessary to produce the minimum velocity difference between the shifted and the reference image. This problem is completely eliminated when using a digital color CCD because no film digitization is required. The performance of a Kodak color CCD for PIV measurements in this experiment is discussed later.

Figure 2 shows a comparison of velocity data obtained with a hot-wire probe and the PIV technique at unforced flow conditions (x/d = 1, Re = 20,000, R = 0.7, and Tu = 1%). The horizontal bars plotted over the PIV results represent the total scatter in velocities observed for an average of 5, 10, 20, and 30 samples. The wide scatter is due to the high Reynolds number, high turbulence levels, and the large-scale turbulent structures of the film-cooling flow. Reasons for the discrepancies shown in Fig. 2 are currently under investigation. However, since only the film-cooling flow was seeded in this experiment, the velocities obtained in the interface region of the unseeded high-speed freestream and the seeded slower-speed film-cooling flow would be expected to deviate from those obtained with a hot-wire probe which cannot distinguish between the two flows. In an earlier experiment for low-Reynolds-number flow where both the ambient freestream and the jet flow were seeded, Gogineni (1993) found excellent agreement between the hot-wire data and the averaged data from 30 PIV samples. In the present experiment, one could argue that 30 images is not sufficient for accurate determination of the mean and fluctuations of this highly unsteady flow field. For investigating this aspect, the rms fluctuation was measured at a constant flow condition, and the results show that the rms deviation approaches 20% as the number of samples is increased. However, a greater number of samples is required to represent the mean flow behavior.

For studying the characteristics of a turbine-blade film-cooling hole environment, the jet injection hole was scaled up by a factor of 35. The stator-wake passage was simulated by periodic forcing of the film-cooling flow at the appropriate reduced frequency (Ω), as described in Bons et al. (1995). Figure 3 shows the results for the simulation of the effect of the stator wake on the film-cooling flow when the film is forced at 20 Hz. These results were recorded on 35-mm film and digitized using a Polaroid SprintScan 35 scanner having a resolution of 2700 pixels/in. This provided a resolution of ~ 3000 x 2000 pixels. These exposures were phase locked to the film-cooling driving frequency, and data were recorded at phase-angle increments of 45 deg. in one forcing cycle. Figure 3 shows the double-exposed PIV images and the corresponding instantaneous velocity distributions at phases of 90 and 180 deg. for R = 0.7, Re = 20,000, and Tu = 1%. The dropouts of velocity vectors in this figure are caused by lack of particles, out-of-plane motions, and unoptimized parameters such as laser-sheet intensity and seeding density. Additional results were reported in detail by Gogineni et al. (1996c).

To overcome some of the obstacles encountered in the film-based PIV and to achieve a quick turn-around time for conducting the experiments under various conditions, a high-resolution Kodak DCS 460 CCD system was implemented. With this system it was possible to optimize the seeding and laser-sheet intensity in near real time, with the net effect being more valid vectors as well as much better definition and resolution of the shear layer. These features are illustrated in Figures 4 and 5, which correspond to unforced film flow at freestream Tu levels of 1 and 17% for R = 0.7 and 1.5. The film-cooling Reynolds number is 40,000. The photographs in Figure 4 have a resolution of 3060 x 2036 pixels--approximately the same as those obtained with 35-mm film after digitization. At this higher Re number, the shear-layer frequency over the film hole increases dramatically. When Tu is increased from 1 to 17% for R = 0.7, no significant change is observed in the eddy sizes in the shear layer after the film-cooling hole. However, for R = 1.5, a significant change takes place. When R is increased from 0.7 to 1.5 at a freestream Tu level of 17%, the roll-up frequency for the shear layer after the film-cooling hole decreases. In the leading-edge exit region of the film-cooling hole, a second parallel shear layer can be detected which may be associated with a separation from the entrance lip of the film-cooling hole, as illustrated in Figures 4(a), 4(b), and 4(c).

Figure 5 shows the instantaneous velocity distribution corresponding to that in Figure 4 which was obtained using a cross-correlation technique (Gogineni et al. 1996c). For improving analysis of the seeded flow field, the output of the linear camera was convolved with a logarithm-like function prior to the cross-correlation analysis. The interrogation domain measured 64 x 64 pixels, corresponding to 2 x 2 mm in the measured flow. For enhancing the overall resolution, the interrogation domains are overlapped by one-half the domain size. For clarity purposes, only one-third of the measured vectors (raw data) are shown in each frame and no post-processing such as interpolation is implemented for these data. The velocity field shown here corresponds to the fixed reference frame; thus, the shear-layer structures are not visible. The large vertical components of the counter-rotating vortical structures formed by the interaction with the freestream can be seen in Figure 5 underneath the shear layer.

Figure 6 shows the vorticity distribution (ω) computed by central differencing of the velocity field of Figure 5. The solid lines indicate positive vorticity, and the dashed lines indicate negative vorticity. As expected, high values of vorticity are found in the shear layer and in the film layer at lower R. When R is increased to 1.5 and Tu to 17%, the vorticity is concentrated in the shear layer far from the surface. The vorticity distribution from the CCD data showed a significant improvement over that resulting from the 35-mm film data (not shown). This can be attributed to the presence of the more valid vectors that resulted from the optimization of PIV parameters.

CONCLUSIONS

Turbine film-cooling data from 35-mm film after digitization and from a 3060 x 2036 pixel CCD camera have been compared and found to have similar spatial resolutions. The CCD allowed optimization of seeding and laser-sheet intensity which resulted in higher vector densities. Hot-wire data and the average of more than 20 PIV frames at x/d = 1 agreed favorably for these highly unsteady flows; however, direct use of mean values for these flows would require an average of more than 30 samples.

PIV has proved to be extremely useful in obtaining additional information on the structure of turbine film-cooling flows such as jet spread, shear-layer growth, and shear-layer frequency. PIV also allows the computation of realizations of vorticity and dissipation for direct comparison with CFD data. PIV has revealed significant changes at the exit of the film hole, reinforcing the importance of modeling flows in these short l/d film-cooling holes.

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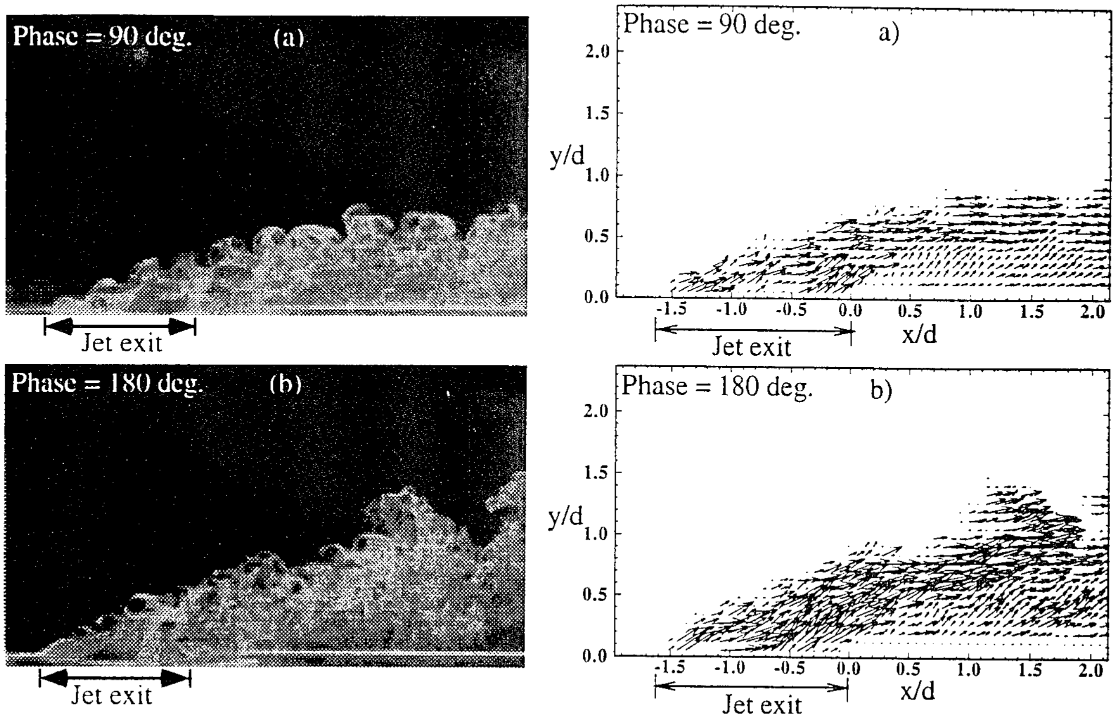

Double exposed PIV images Instantaneous velocity distribution

Figure 3. Simulated turbine vane wake (Re = 20,000, R = 0.7, Tu = 1%, f = 20Hz)

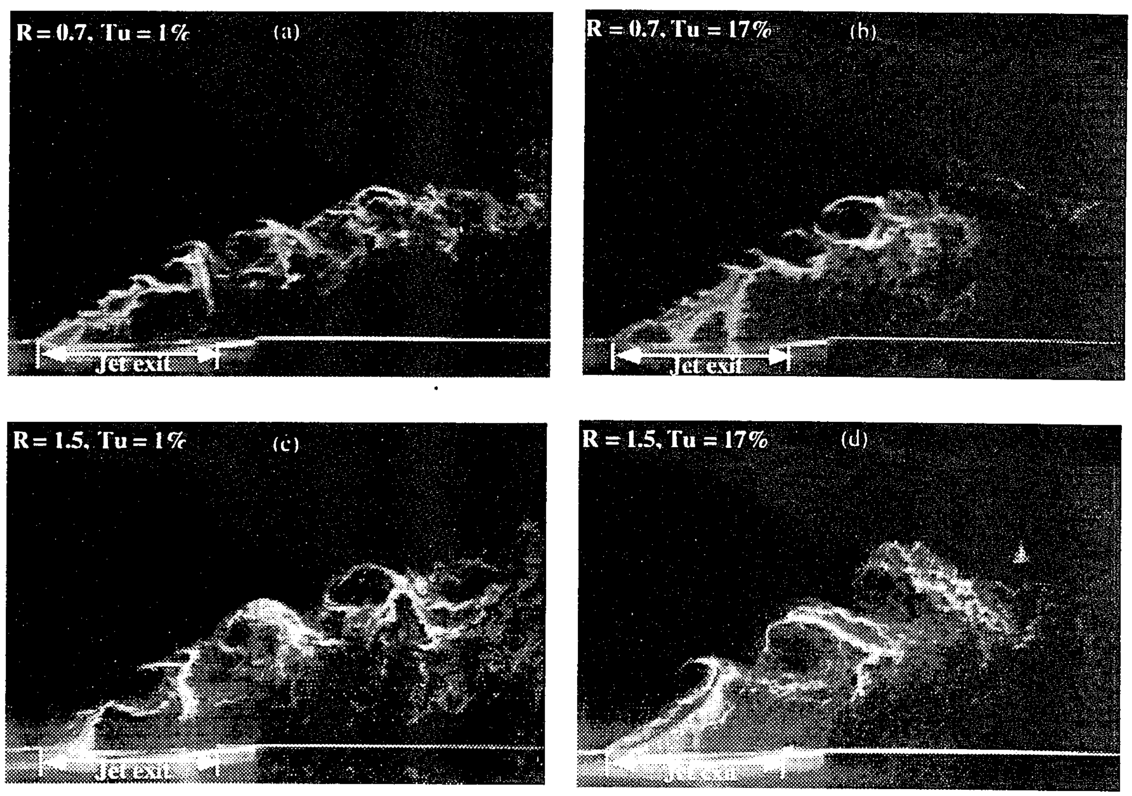

Figure 4. Simulated turbine film-cooling flows using CCD sensor (Re = 40,000)
(Double exposed PIV images)

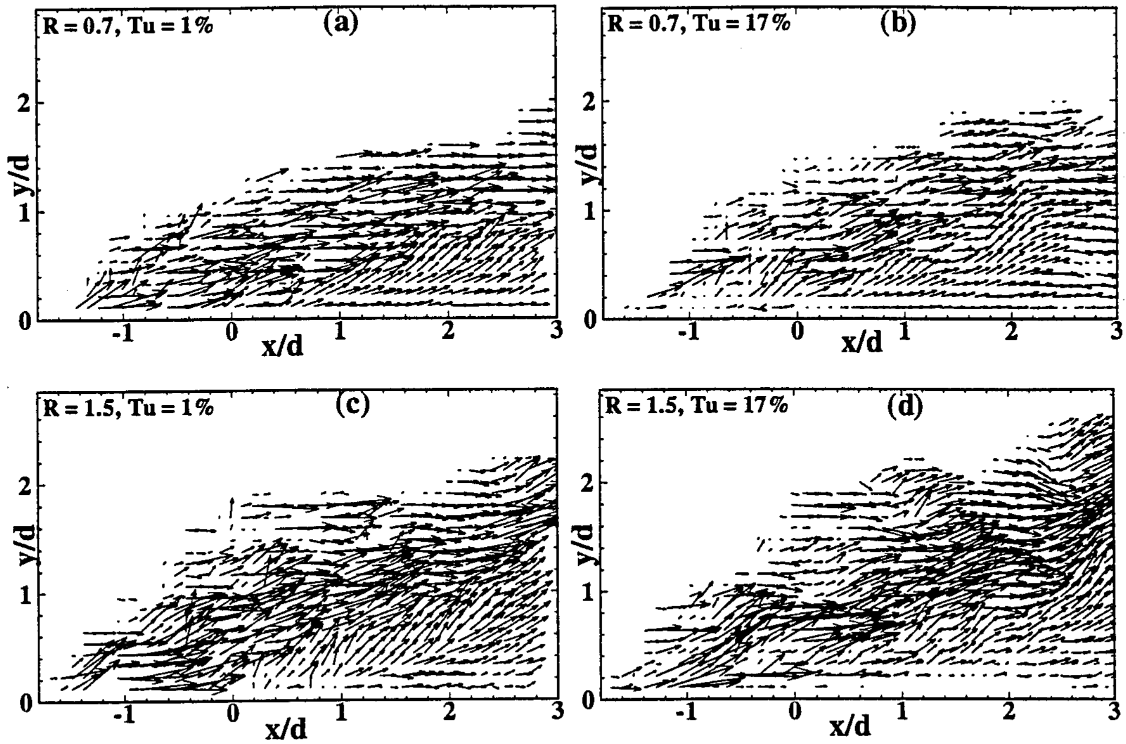

Figure 5. Instantaneous velocity distribution (Re = 40,000)

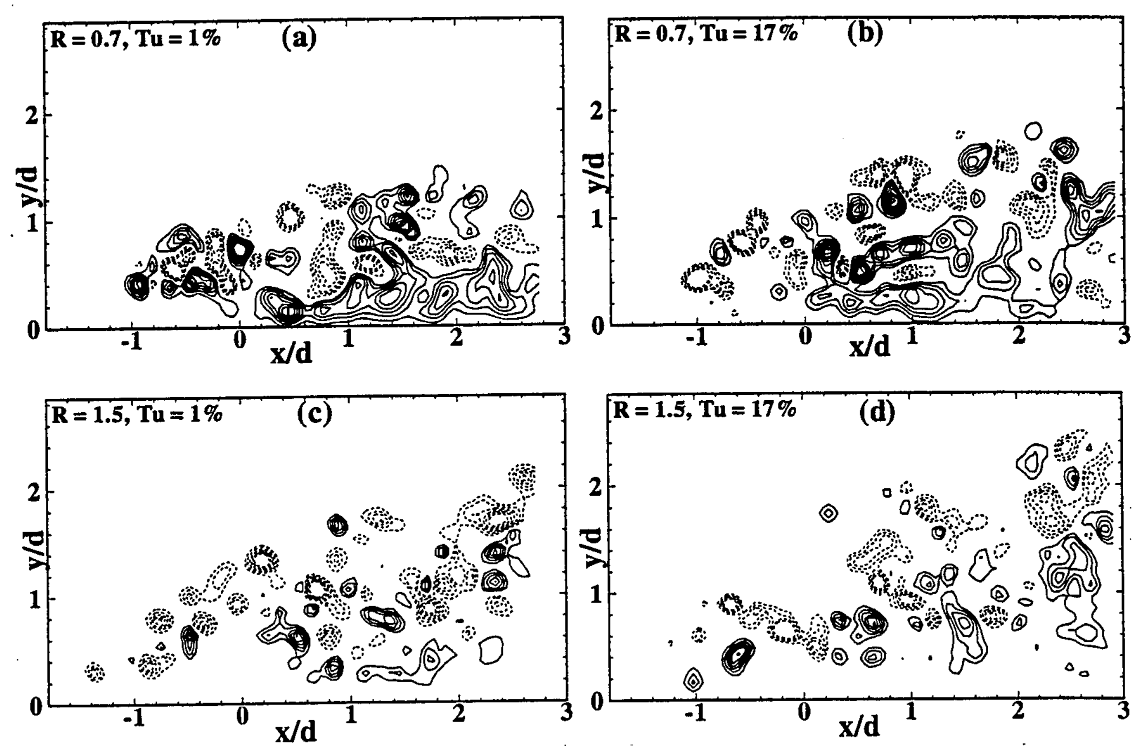

Figure 6. Instantaneous vorticity distribution (Re = 40,000)